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# SPACE COMPUTER CORPORATION

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## ALGORITHMS FOR SPACE-BASED INFRARED SURVEILLANCE

Final Technical Report

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Naval Research Laboratory
ATTN: Code 6521 (Dr. Joseph Michalowicz)
Washington, DC 20375-5000

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2800 Olympic Boulevard • Suite 104 • Santa Monica, California 90404—4119
(310)829—7733 Fax (310)829—1694
Internet spacecc@cerf.net

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**19. ABSTRACT (Continue on reverse if necessary and identify by block number)**

The objective of the study summarized in this report was to develop and evaluate algorithms for detecting low-observable air vehicle targets from a space-based imaging infrared sensor. The effort consisted of theoretical and simulation studies in three areas: frame registration, velocity filtering, and multispectral processing. In the first area, a generalization of the well-known phase-correlation approach for frame registration and clutter suppression was developed. This new approach is significantly more accurate and robust than the standard correlation technique. Also, an improved approach to image interpolation for multi-frame clutter suppression applications was formulated. A major feature of this new approach is the application of the same in-band filtering to every registered frame in order to minimize structured clutter leakage when the frames are differenced. In the second area (velocity filtering), the standard velocity filter approach was extended from fixed-contrast to variable-contrast targets. In the third area (multispectral processing), techniques were developed for clutter suppression and target enhancement for both stationary and moving targets. (Continued on reverse)

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|---|---|---|
| Dr. Joseph Michalowicz | (202) 767-9386 | Code 6521 |

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## Block 19. ABSTRACT (continued)

Three basic algorithms were formulated and evaluated: a minimum-clutter processor, a spectral matched filter, and a fully-adaptive spectral filter (based on work by I.S. Reed and Xiaoli Yu). Modeling procedures were developed for the determination of detection performance under a wide range of conditions as well as for waveband selection criteria.

This report contains summaries of each of the three technical areas described above, and summaries of nine technical reports and papers produced under this contract.

# 1. INTRODUCTION AND SUMMARY

The objective of the study reported in this document was to develop and evaluate algorithms for detecting low-observable air vehicle targets from a space-based, imaging infrared sensor. The effort consisted of theoretical and simulation studies in three areas: frame registration, velocity filtering, and multispectral processing. These studies can be summarized as follows.

## 1.1 Frame Registration

A fundamental problem in infrared surveillance is the detection of low-observable moving targets in spatially-varying background clutter. Multi-frame or temporal clutter suppression often provides an effective solution to this problem. In its simplest form, this processing involves subtracting successive pairs of frames to suppress the mean background level on a pixel-by-pixel basis. To avoid significant clutter leakage in the difference frames, the background scene in the frames to be subtracted must be spatially registered, often to sub-pixel accuracy. This creates a requirement for a processing procedure which measures the apparent displacement of the background and resamples the image frames so that the background appears to be motionless.

For precision motion measurement, we developed a generalization of the well-known phase correlation approach for frame registration which is significantly more accurate and more robust than standard correlation techniques. Key features of our approach include the use of simple polynomial interpolation for determining the location of the phase correlation peak, and the use of a pre-computed bias correction dependent only on known signal processing parameters.

An improved approach to the image resampling problem for multi-frame clutter suppression applications was also formulated during the program. A major feature of this new approach is the application of a nearly equivalent in-band filtering operation to each co-registered frame pair to be differenced. True interpolators tend to perform sub-optimally in this respect because they apply no filtering at all to zero-shifted reference frames. Better suppression performance can be obtained by using FIR interpolation kernels that apply filtering at all shifts, including zero. Such kernels must have very low out-of-band sidelobes, so that leakage due to subtraction of differently-phased foldover components from differently-shifted frames will be below the sensor noise limit.

## 1.2 Velocity Filtering

Velocity filtering is a signal processing technique for integrating the energy in a moving target from one frame to another to increase the signal-to-noise ratio prior to detection. This technique was originated by Prof. Irving S. Reed at the University of Southern California and further developed by Space Computer Corporation under contracts sponsored by SDIO, DARPA and others. During the study reported in this document, the velocity filter approach was extended from fixed-contrast targets to variable-contrast targets. In particular, several variations of an adaptive velocity filter for such targets in unknown backgrounds were developed. These variations differ according to (1) whether the input frames result from frame stack mean suppression or from pairwise frame differences, and (2) whether or not the

temporal clutter correlation introduced by the frame whitening process is accounted for in the filter. Analytical results predicted that it would be possible to achieve the same detection performance using either pairwise frame differences or a co-registered, mean-suppressed frame stack (although the required computations would be greater with the pair differences). Experiments on simulated frame differences with injected occlusion targets confirmed these predictions. This result is important because it shows that pairwise-difference frames, which appear to be easier to accurately co-register than stacked frames, can provide essentially the same performance as stacked frames.

## 1.3 Multi-Spectral Studies

Multi-spectral processing utilizes information from imaging sensors which collect data in several different wavebands. This technique, which provides clutter suppression and target enhancement by exploiting spectral differences between the target and the background, is of major importance because it is applicable to stationary as well as moving targets. Multi-spectral processing exploits the high band-to-band correlation of natural background emission in the thermal IR region that has been observed empirically. It also relies on some form of target/background "coloring" mechanism. There are three possible physical mechanisms for achieving useful color differences between a target and its background in the thermal IR region:

1) Physical coloring introduced by different emissivity profiles (e.g., a selectively-radiating target viewed against a blackbody background);

2) Temperature differentials between the target and background, leading to differences in energy distribution between bands;

3) Atmospheric coloring introduced by differences in the lengths of the transmission paths from the target and background, respectively, to the sensor.

It is anticipated that the latter two phenomena will be of particular utility for space-based surveillance applications, especially for those in which high-altitude aircraft targets are of major interest.

We have evaluated three multi-spectral processing algorithms for the detection of targets in clutter:

1) A minimum-clutter processor, in which the spectral difference is weighted to minimize clutter power in the output image;

2) A spectral matched filter, i.e., a linear filter which maximizes the signal-to-clutter ratio (SCR) for targets with a specified spectral signature;

3) A fully-adaptive spectral filter (also known as the Reed-Xiaoli or "RX" algorithm); this is a non-linear algorithm which discriminates features of a given shape that have statistically significant color differences relative to the local background.

These algorithms were evaluated for dual-band processing to determine the SCR gain as a function of the "color ratio" (the ratio of the SCRs in the two bands) for various values of the band-to-band correlation coefficient. The results were then employed to determine detection performance and to develop criteria for waveband selection.

Multispectral data employed for analysis included LWIR background scenes collected by the NASA TIMS and the DARPA HICAMP infrared sensors. These data were combined with LOWTRAN

and MODTRAN atmospheric absorption model data to predict performance for various aircraft detection scenarios. We also processed a dual-band HICAMP data set in which a colored moving target (a small helicopter) was viewed against a vegetation clutter background. In this case, we found that the optimum weighted-band differencing algorithm provided 26 dB of clutter suppression with practically no attenuation of the target signal.

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# 2. SUMMARY OF REPORTS AND PUBLISHED PAPERS

For detailed descriptions of the technical results obtained under this contract, see the individual reports and papers which are summarized below.

## 2.1 "SCR Loss Due to Focal-Plane Sampling" (Report SCC-R-181-1, September 1990)

The clutter-limited performance of the velocity filter and related detection schemes depends on the available SCR. One source of SCR degradation is aliasing introduced by sampling the focal-plane image with a discrete set of detectors. This report presents the results of a sensitivity analysis to quantify the loss due to this effect. It is shown that: (1) the focal-plane detector spacing should not be much larger than about one-half the size of the optical blur circle, and (2) a detector-array design with an intermediate fill factor, such as 0.5, will be more robust under unknown clutter conditions than a design with a very small or a very large fill factor.

## 2.2 "Focal-Plane Sampling Loss for Square Detectors" (Report SCC-R-181-2, 3 October 1990)

The work reported here shows that the focal-plane sampling loss is not highly sensitive to the assumed shape of the detector response (Gaussian or square), so long as the respective spatial frequency passbands of the detectors are nearly equal.

## 2.3 "Phase Correlation and Optimum Displacement Estimation" (Report SCC-R-181-3, October 1990)

This report outlines the theoretical basis for the phase correlation approach and discusses implementation alternatives. A specific relationship is established between phase correlation and an optimum (maximum likelihood) displacement estimator for a random scene immersed in Gaussian sensor noise. The mathematical form of the optimum estimator provides strong theoretical motivation for the use of nonuniform cross-spectrum phase weighting that is a function of the power spectral densities of the background scene and the sensor noise. It further suggests that the 2-D displacement should be measured directly in terms of the location of the phase correlation peak, rather than indirectly via a weighted least-squares fit to the cross-spectrum phase function. This direct measurement approach also avoids potential problems introduced by phase ambiguity in cases where frame shifts greater than one pixel are encountered.

The practical problem of interpolating the discrete phase correlation peak to sub-pixel accuracy is also addressed. An interpolator based on a separate parabolic fit to the peak is utilized for computational simplicity. The resulting displacement estimates are shown to be biased, but the bias is a function of known signal processing parameters which do not depend on the unknown spatial frequency content of the underlying scene. The bias can therefore be predicted in advance and corrected in real time by means of a table lookup. Simulation experiments show that the systematic measurement error associated with this technique is practically nil.

**2.4 "Interim Technical Review" (Program Review No. 1) (Report SCC-PR-181-1, 13 December 1990)**

This technical review discusses work on algorithms for frame registration and velocity filtering. It describes a generalized frame registration algorithm which accounts for arbitrary (small) motions, including rotation and distortion as well as translation. This algorithm utilizes blockwise phase correlation, 2-D thin-plate spline fitting, and a FIR interpolation filter. The algorithm is fully adaptive in the sense that no prior information about the encounter geometry, platform motion or sensor boresight direction is required. Key implementation issues for phase correlation include frame weighting and/or zerofill, use of cross-spectrum phase weighting, and correlation peak measurement vs. least-squares fit. It is concluded that all frames to be registered (including the zero-shift reference) should ideally be identically filtered by the interpolation kernel. This requires use of a filter kernel with very low out-of-band sidelobes so that in-band mismatch due to different resamplings will be negligible. Registration examples used in the study include (1) a simulated flyover sequence based on a TIMS LWIR scene of Mono Lake, CA, (2) a video data sequence of night sky scenes taken with a TV camcorder from an aircraft, and (3) a 10-frame sequence of LWIR scenes from a simulated SPIRE LWIR space-based sensor.

The velocity filter algorithm studies include a general matched filter for point targets, several velocity filters for specific cases (for both mean-suppressed frame stack and pairwise difference frame approaches), and adaptive velocity filters for variable contrast targets in unknown backgrounds. It is shown that it is possible to achieve the same SCR using either mean-suppressed frames or frame-pair differences.

**2.5 "Comparison of Interpolation Kernels" (Report SCC-R-181-5, 1 February 1991); also "Monthly Status Report No. 4" (8 January 1991)**

These reports contain comparative evaluations of various frame interpolation kernels for use in clutter suppression processing. Accurate interpolation or resampling of the discrete frames is critical to the performance of clutter suppression schemes based on frame differencing or frame stack mean removal. Even if the local registration error measurements were perfect, a poorly implemented interpolation step can introduce significant noise into the difference frames. The use of separable sliding-window FIR interpolators is a viable approach to the problem, providing that a suitable interpolation kernel is selected. The desired characteristics of an interpolation kernel are linear phase, flat in-band response and low out-of-band sidelobes. A flat linear-phase passband reduces the signal distortion due to interpolation filtering. Low sidelobes minimize the amount of interpolation "noise" introduced by aliased components that fold into the original band when the filtered signals are decimated at or near the original sampling rate.

It is of critical importance to apply the same in-band filtering to each frame to be differenced or mean-suppressed. Otherwise, clutter leakage will occur due to mismatch in the spatial frequency content of the interpolated frames. This condition can be satisfied exactly if each frame is resampled in precisely the same way; however, this is not generally possible. The problem is that the different resamplings needed for registration apply different phase shifts to the out-of-band components of the interpolated scene. These components, which fold back into the original band upon decimation, constitute a source of

"noise" which varies in a rather unpredictable way from one frame to another. A practical solution to this problem is to choose an interpolation kernel that attenuates the out-of-band signal components to the point where they are well below the level of the sensor noise. For a typical IR detection application where the a-c clutter-to-noise ratio is on the order of (say) 10, this would imply the use of FIR filter kernels with sidelobes on the order of 25-30 dB or better.

These documents present an evaluation of a variety of interpolation filter kernels, including 4-point cubic convolution, 4-point cubic B-spline, 4-point custom FIR filter, 5-point DFT filter, and 6-point DFT filter. It turns out that LF filters proposed by NRL provide excellent performance for low-frequency signals. The reason for this can be inferred directly from their out-of-band sidelobe response: specifically, the presence of very wide nulls at integer multiples of the pixel rate. However, the cubic B-spline filter is the best interpolation filter with respect to the performance measures used thus far.

### 2.6 "Program Review No. 2" (Report SCC-PR-181-2, 23 April 1991)

This document deals almost entirely with multi-spectral performance modeling. It contains, first, a review of the multi-spectral processing concept and the various multi-spectral algorithms evaluated. This is followed by a performance prediction analysis for a scenario in which multi-band TIMS sensor data are used for the background (a high desert scene) against which two simulated aircraft targets are viewed: a cold target at high altitude and a hot target at very low altitude. The results show that large spectral processing gains are possible for the high-altitude target, with modest gains possible for the low-altitude target. In both cases, the best performance is obtained with the second band centered on the skirt of the atmospheric window, and with a high band-to-band background correlation coefficient.

Measured spectral correlation coefficients are then presented for a variety of multi-band IR scenes taken with the TIMS and HICAMP sensors. The TIMS backgrounds and their associated spectral correlations are as follows: dry vegetation (0.985 to 0.996), high desert (0.989 to 0.998), grass/woods (0.923 to 0.977), and cultural (0.922 to 0.974). A HICAMP vegetation scene (LWIR/MW pair) shows a correlation of 0.970. Further information is presented on decorrelation mechanisms, on spectral correlation prediction for IR emission, and on measured emissivity statistics.

The remainder of this document deals with multi-band frame sequence processing, i.e., the use of *both* spectral and temporal IR data for clutter suppression and target enhancement. Various approaches are presented, including cases in which the spectral clutter suppression either precedes or follows the temporal processing. These techniques, which apply to both stationary and moving targets, require both spectral and temporal frame registration.

### 2.7 "Program Review No. 3" (Report SCC-PR-181-3, 9 October 1991)

This review deals primarily with precision frame registration and multi-spectral performance monitoring. It contains a review of the frame registration studies carried out to date, including a detailed phase correlation error analysis and procedures for bias correction when small subframes are used for displacement measurement. It is shown that finite-frame effects are the dominant source of bias in phase correlation shift measurements, that the SQRT (Hanning) or cosine lobe is the best window to use for

subframe truncation, that a 64x64 subframe size is better than a 32x32 one, that bias correction procedures based on estimated power spectra can reduce measurement bias and RMS error, and that registration accuracies on the order of 0.003 to 0.01 pixel are readily achievable.

The multi-spectral topics discussed in this document are: atmospheric models, performance prediction, TRAIN processing results and multi-spectral data sources. It is shown that the MODTRAN computer code is a clear improvement over LOWTRAN for high-resolution atmospheric modeling, and that the FASCOD2 code is best for propagation through the upper atmosphere. Additional information is presented on processing experiments with HICAMP and other data.

## 2.8 "Filtering Interpolators" (Report NRL/FR/6521-92-9505, 20 July 1992)

This internal NRL report, authored by Robert L. Lucke of NRL and Alan D. Stocker of Space Computer Corporation, deals with the interpolation problem for frame registration and clutter suppression. Interpolation error contributes to clutter leakage through a frame differencing signal processor, especially for highly structured scenes. This error can be reduced by an order of magnitude by applying a spectral filter to the unshifted frame that matches the filtering effect of applying the interpolator to the frame that is shifted. The signature reduction penalty for point targets is rarely as large as a factor of two, leading to substantial improvements in signal-to-clutter ratios when the interpolation error is the dominant source of clutter. Parameterized families of local convolutional interpolators (polynomial and trigonometric) that can be adjusted to the particular target/clutter/noise combination of interest are presented. For spline interpolation applications, the trigonometric family yields an alternative to the cubic B-spline kernel.

## 2.9 "Filtering Interpolators for Frame Differencing Signal Processors" (technical paper to be published in the August 1993 issue of the IEEE Transactions on Signal Processing)

This paper is authored by Robert L. Lucke of the Naval Research Laboratory and Alan D. Stocker of Space Computer Corporation. It shows how interpolation error contributes to clutter leakage through a frame differencing signal processor, especially for highly structured scenes. For low sampling rates, interpolation error can be reduced by as much as an order of magnitude by applying a spectral filter to the unshifted frame that matches the filtering effect of applying the interpolator to the frame that is shifted. The signature reduction penalty for point targets is rarely as large as a factor of two, leading to substantial improvements in signal-to-clutter ratios when interpolation error is the dominant source of clutter. Parameterized families of local interpolators (polynomial and trigonometric) that can be adjusted to the particular target/clutter/noise combination of interest are presented.